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Locating near-surface scatterers using non-physical scattered waves resulting from seismic interferometry

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ABSTRACT

We use controlled-source seismic interferometry (SI) and inversion in a unique way to estimate the location of near-surface scatterers and a corner diffractor by using non-physical (ghost) scattered surface and body waves. The ghosts are arrivals obtained by SI due to insufficient destructive interference in the summation process of correlated responses from a boundary of enclosing sources. Only one source at the surface is sufficient to obtain the ghost scattered wavefield. We obtain ghost scattered waves for several virtual-source locations. To determine the location of the scatterer, we invert the obtained ghost traveltimes by solving the inverse problem. We demonstrate the method using scattered surface waves. We perform finite-difference numerical simulations of a near-surface scatterer starting with a very simple model and increase the complexity by including lateral inhomogeneity. Especially for the model with lateral variations, we show the effectiveness of the method and demonstrate the estimation of the subsurface location of a corner diffractor using S-waves. In all models we obtain very good estimations of the location of the scatterer.

1. Introduction

The investigation and detection of near-surface structures such as cavities, caves, sinkholes, tunnels, mineshafts, buried objects, archeological ruins, water reservoirs and similar is important to mitigate geo- and environmental hazards (Culshaw and Waltham, 1987). These near-surface structures, (henceforth called scatterers) may pose risk during and after the construction of buildings, transportation ways (roads, highways, railways) or power plants (wind, solar, etc.), which are spread on wide areas. Furthermore, these scatterers can be affected by the changes in the hydraulic regime, earthquakes and change of the loading on the soil and thus may cause risk. Therefore, the detection, monitoring and stabilization of this type of weak zones is important to prevent environmental and geo hazards.

Especially, the detection of natural (karstic structures and caves) and man-made (tunnels, mine shafts and galleries) cavities is widely studied in the literature. Both numerical and/or field experiments are performed for this purpose. Several geophysical methods are available for investigation of the near-surface structures and each has advantages and disadvantages (McCann et al., 1987). The success depends on the resolution and penetration achieved by each method. Ground penetrating radar (GPR) (Al-fares et al., 2002; Nuzzo et al., 2007), microgravity and multi-channel analysis of surface waves (Debeglia et al., 2006; Samyn et al., 2012; Xu and Butt, 2006), seismic refraction and electric resistivity (Cardarelli et al., 2010; Nuzzo et al., 2007), seismic refraction only (Engelsfeld et al., 2008, 2011), are some examples for the exploited methods that are used for detecting the cavities. Some examples of geological studies on cavities and related geohazards are found in Culshaw and Waltham (1987), Woodcock et al. (2006), Edmonds (2008) and Khomenko (2008).

In seismic methods, a high-accuracy subsurface image of the shallow objects can be obtained using reflected body waves. This, though, requires high-resolution data acquired in a dense spatial array. These are not easily available for shallow-seismic applications. Furthermore, it might not always be possible to place active sources above the target scatterer or even close enough to it. In such cases, using sources away and having the generated wavefields propagate through unknown inhomogeneities might distort the results significantly. Surface waves are widely used in global, exploration and near-surface geophysics. A notable difference in the applications is the frequency content and the array aperture of the measurements that affect the investigation depth. The dispersive property of surface waves allows the estimation of the S-wave velocity structure and attenuation of shallow layers. In global seismology, surface waves are used to investigate the crust and upper-mantle structure (e.g. Chang and Baag, 2005; Cong and Mitchell, 1998; Kovach, 1978) and the source properties of seismic events (e.g. Canıtez and Toksöz, 1971; Ekström, 2006). In geotechnical engineering, S-wave velocity estimation from surface waves has become a popular tool and different active and passive-source techniques are applied (Bozdag and Kocaoglu, 2005; Foti, 2000; Kocaoglu and Fırtana, 2011; Leparoux et al., 2000; Nazarian et al., 1983; O'Neill, 2003; Park et al., 1999; Rix et al., 1998; Socco and Boiero, 2008; Socco et al., 2009, 2010) to obtain the near-surface

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properties of the medium. The surface-wave methods work under the assumption of laterally homogeneous stratified layers. Therefore lateral inhomogeneities, such as cavities or varying overburden thickness and steeply dipping bedrock cause difficulties in the estimation of the velocity structure and in the evaluation of the lateral inhomogeneities on the dispersion curve. However, Nasseri-Moghaddam et al. (2005), Bodet et al. (2010) and Boiero and Socco (2010) show the possibility of exploiting surface-wave dispersion curves to investigate voids and lateral variations of the subsurface.

Another methodology that is used for detecting the near-surface structures is that with scattered waves. Scattering of P-waves are used by Grandjean and Leparoux (2004), Gelis et al. (2005), Rodríguez-Castellanos et al. (2006), Mohanty (2011); coda waves are used by Mikesell et al. (2012); and scattered surface waves are used by Snieder (1987), Herman et al. (2000), Leparoux et al. (2000), Campman et al. (2004), Grandjean and Leparoux (2004), Gelis et al. (2005), Campman and Riyanti (2007), Kaslilar (2007), Xia et al. (2007), Chai et al. (2012). Based on seismic interferometry the scattered surface waves are studied in detail by Halliday and Curtis (2009).

We propose to use non-physical (ghost) scattered body and/or surface waves, obtained by seismic interferometry (SI), in an inversion scheme to estimate the location of a scatterer (Harmankaya et al., 2012a,b). The appearance of the ghost scattered waves is explained later in this section. SI traditionally refers to the method of retrieving the interreceiver wavefield by cross-correlating the wavefields recorded at each of the receivers (e.g. Snieder, 2004; van Manen et al., 2006; Wapenaar, 2004; Wapenaar and Fokkema, 2006). SI can be divided into controlled-source and passive methods. Controlled-source SI (Schuster et al., 2004) involves cross-correlation followed by summation over different controlled source positions at a boundary, while passive SI is the methodology of turning passive seismic measurements, like ambient noise and earthquakes, into impulsive seismic responses (Draganov et al., 2007, 2009; Roux et al., 2005; Ruigrok et al., 2010; Shapiro and Campillo, 2004). While SI has proven useful in retrieving surface-wave waveforms from passive noise sources (e.g. Halliday and Curtis, 2008; Sens-Schönfelder and Wegler, 2006; Snieder and Wapenaar, 2010), it is also shown that active-source signals can be used to synthesize interreceiver surface-wave estimates, which can be used, for example, for predictive ground-roll removal (Dong et al., 2006; Halliday et al., 2007, 2010).

To obtain the complete Green's function between the receivers whose recorded responses we cross-correlate, the boundary sources (primary or secondary) effectively need to enclose these receivers (Wapenaar and Fokkema, 2006). When the receivers are not equally illuminated from all directions by the boundary sources, ghost arrivals will appear in the SI result (Snieder et al., 2006). Furthermore, the physical arrivals might not be retrieved correctly. When using active sources at the surface, as is the standard practice for near-surface seismics, reflection ghosts will nearly always be present. The reflection ghosts are arrivals retrieved from the correlation of two reflected events in the active data, whose traveltimes correspond to reflections as if measured with sources and receivers redatumed in the subsurface at the levels of reflectors (Draganov et al., 2012; King and Curtis, 2012). This type of ghosts is called spurious reflections by Snieder et al. (2006). The limited number of the used sources might make the problem with the retrieved reflection ghosts even worse.

One way of addressing this problem is to try to retrieve only specific parts of the Green's function, for example only surface waves. For this, having sufficient boundary sources only in the stationary-phase regions for the retrieval of these specific parts would be enough (Snieder, 2004). For an inhomogeneous medium, the stationary-phase region for retrieval of direct surface waves between two receivers lies along the ray connecting the receivers and away from them. The boundary sources need to be present at the surface, but also down to a certain depth, depending on the specific medium characteristics. When only sources at the surface are used, the fundamental mode of the surface wave will be retrieved correctly, while the higher modes will be retrieved incorrectly (Kimman and Trampert, 2010). For retrieval of body-wave reflections between the two receivers at the surface, the stationary-phase region lies in the subsurface along the specular ray for that reflection arrival. The specular ray is the line in the subsurface, along which a wavefield will first be recorded at one of the receivers and after reflecting from the target subsurface reflector will be recorded at the second receiver. Using stationary-phase arguments, it can be shown that the subsurface boundary-source positions can be projected to surface positions along the specular-ray paths. This process, though, has as a consequence that reflection ghosts will be retrieved (Draganov et al., 2012; King and Curtis, 2012).

Retrieval of scattered surface waves follows the same logic as the retrieval of reflections, but the specular ray is along the surface. Halliday et al. (2010) show a field application of SI for retrieval of direct and off-line scattered surface waves by using a densely sampled 2D patch of active sources. Unfortunately, in near-surface seismics such dense source geometries are not common. Most likely, the active sources will be along a line or along several lines with a certain distance between them. This would mean that off-line scatterers would most likely result in the retrieval of ghost scattered surface waves. A subsurface scatterer will nearly always give rise to ghost scattered body waves.

In the following, we show that a limited number of available active surface sources is sufficient for locating a subsurface scatterer and estimating its location. We use modelled surface and body waves and show that even one active source is sufficient to obtain ghost scattered waves. In the next section, the calculation of the ghost scattered wavefield and the estimation procedure for the location of a point scatterer is given in detail using a dataset modelled according to an integral representation of the scattered wavefield. For inversion of the obtained ghost field, we use Singular Value Decomposition (SVD) and as a complementary method — the grid search method. The qualities of the estimations are provided by preparing the model resolution, data resolution and model covariance matrices. In Section 3, we test our method using finite-difference modelled data for models with increasing complexity — scatterer in a halfspace, scatterer and a corner diffractor in a medium with lateral velocity variation. As SI effectively redatums sources (or receivers) from places away from the scatterers to the target area (the location close to the structure of interest), the unwanted extra effects, due to propagation from sources through the laterally changing medium to the receivers close to the target area, are eliminated and the scatterer location can be estimated successfully. The discussions and conclusions are given in Sections 4 and 5, respectively.

2. Method

2.1. Ghost scattered waves obtained by SI

SI traditionally refers to the method of retrieving the interreceiver wavefield by cross-correlating the wavefields recorded at each of the receivers (e.g. Snieder, 2004; van Manen et al., 2006; Wapenaar, 2004; Wapenaar and Fokkema, 2006). In non-ideal situations apart from the true wavefield non-physical events will also occur. In this study, we use non-physical scattered body and surface waves in inversion to estimate the location of a scatterer. SI is applied to the scattered wavefield obtained from the seismic records of the original geometry by using only one source and by cross-correlating the reference trace d^{VS} (the trace at the virtual-source position) with the rest of the traces, d^i, which are present on the seismic record. This relation is

$$C_{d^i d^{VS}}(\tau) = \sum_n d^i(t_n) d^{VS}(t_n + \tau). \quad (1)$$

Note that the complete SI relation, as derived by Wapenaar and Fokkema (2006) requires a second summation over active sources